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Performance measurements of a self-referencing interferometer wavefront sensor with optical amplification (Preprint)

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ABSTRACT

The Self-Referencing Interferometer Wavefront Sensor (SRI WFS) has been shown to outperform conventional wavefront sensors in strong scintillation environments. Recently, the Starfire Optical Range has developed a prototype SRI to evaluate its performance. This paper discusses the purposes of optically amplifying the reference beam. Specifically, it addresses regions of operation where gain improves signal-to-noise ratio (SNR) values, and thus the SRI WFS performance. Conditions are also addressed when Amplified Spontaneous Emission (ASE) from the optical amplifier degrades the overall signal, resulting in less than acceptable signal-to-noise ratios. Laboratory measurements of SRI WFS performance with an optical amplifier are presented.

Keywords: adaptive optics, wavefront sensors, optical amplifiers, scintillation

1. INTRODUCTION

Wavefront sensors are an integral component in modern adaptive-optical systems. Wavefront sensors developed prior to the Self Referencing Interferometer Wavefront Sensor (SRI WFS), such as the Shack-Hartmann WFS, have limited application in strong scintillation environments, as the system's performance degrades due to branch points in the wavefront phase.[1–3] The SRI WFS directly measures the average wavefront field of the incoming light over each subaperture of the WFS, making it theoretically immune to scintillation.[4] Optical amplification of the WFS has been theoretically shown to enhance performance in the high scintillation regime.[5] By investigating the benefits and drawbacks of optical amplification, laboratory results are presented to validate increased performance of the SRI WFS in strong scintillation.

This paper is broken down as follows. In section 2, the theory and mechanics of the SRI WFS are addressed. A discussion of noise sources and the importance of gain within the SRI WFS system are presented in section 3. A description and comparison of traditional optical amplifiers used within the SRI WFS system are discussed in section 4. The experiment to test and characterize the contributions of gain is detailed in section 5. Experiment results and analysis are presented in section 6, followed by closing comments in section 7.

2. OVERVIEW OF THE SRI WFS

Figure 1 depicts a conceptual view of the SRI WFS with optical amplification. The incoming beam, U_0, is split into two beams: a reference and signal, U_r and U_s, respectively. From there, the reference beam is coupled into a single mode fiber, amplified, and recombined with the signal to create interference fringes on the WFS camera. Due to the broadband nature of Amplified Spontaneous Emission (ASE), several components are needed in addition to the amplifier. After coupling into the single mode fiber, the resulting beam passes through an isolator, which will prevent ASE from travelling backwards up the optical path, degrading the original signal, and corrupting other detectors in the system. The beam is then optically amplified to improve the intensity of the signal. After the amplifier, a spectral filter is placed in the beam path to eliminate the extraneous wavelengths that add noise to the WFS measurements. After the spectral filter, the remaining portion of the reference beam is phase shifted to provide the different interference patterns the SRI WFS will use to reconstruct the wavefront phase.

There are several methods of phase shifting that can be used to capture the necessary interference patterns. These methods include spatial phase shifting, temporal phase shifting, and a combination of the two.[6] Spatial phase shifting creates the interference patterns instantaneously, with four different beams shifted at varying degrees and sent to different detectors. Temporal phase shifting takes the beam and phase shifts it in sequential

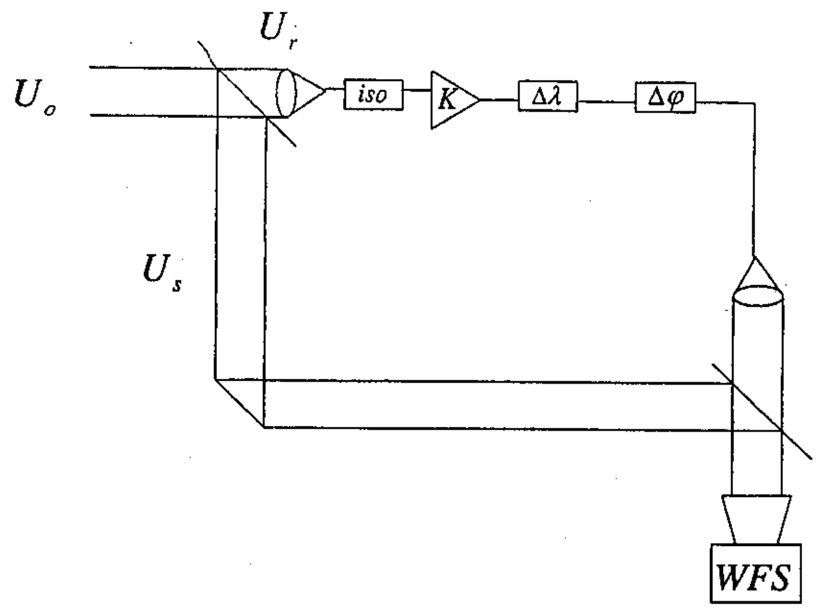

Figure 1. Conceptual diagram of the SRI WFS with an optical amplifier.

integration periods of time, and each image is recorded on a single detector. Spatial-temporal phase shifting combines both methods by capturing two images at two consecutive integration periods. Discussion and comparison of phase shifting techniques is discussed in a separate paper. Currently, the SRI WFS employs a fiber phase shifter that facilitates temporal phase shifting. After being phase shifted, the reference beam recombines with the signal beam, and the resulting beam is sent to the SRI WFS camera to create detectable interference patterns.

The ASALT lab operates with a signal wavelength of 1.55 μm. This is due to readily available parts, developed with technology matured by the telecom community. Both the semiconductor optical amplifier (SOA) and the erbium doped fiber amplifier (EDFA) employ a gain meduim operating at a signal wavelength of 1.55 μm.

3. GAIN

An appropriate amount of gain helps the SRI WFS by boosting the intensity of the beam to overcome read noise of the WFS camera. In high scintillation environments or in situations with little illumination, the reference beam may not be intense enough to overcome read noise. Depending on the scenario, the beam may fluctuate in intensity, making tracking of the beam and detection of the interference fringes at the WFS difficult. Poor tracking prevents the necessary system stability to close and maintain the AO loop. Additionally, shallow fringes may preclude the possibility of reconstructing the wavefront phase from the interference pattern. Just as a generic amplifier increases the intensity of a signal, an optical amplifier increases the intensity of the optical signal. With a stronger reference beam, the depth of the fringes created on the SRI WFS can become significantly greater than the background level of noise. This gives the needed signal to noise (SNR) levels for input to the WFS reconstructor; a necessary prerequisite for closed loop AO stability. Despite the benefits of gain in a closing an AO loop, there are drawbacks as well. Too much gain may boost the beam so much that it will saturate the camera, thereby impairing the ability to take accurate measurements of the fringes.

3.1. Drawbacks of Optical Amplifiers

While amplifiers theoretically offer improved performance to the SRI WFS, they have some drawbacks. Additional components are required to mitigate spurious noise caused by the amplifying medium. As described in section 2, an isolator is vital to preventing incoherent interference with the amplified reference beam and the optical signal. A spectral filter can eliminate much, but not all, of the ASE from the remainder of the optical

path. Adding these elements to the system introduces sources of loss that decrease the overall signal, effectively lowering the gain of the amplifier. Even with splice connections, insertion losses and interfaces impair the system efficiency. Losses from the spectral filter, the isolator, and connections to these components are typically on the order of 4 dB.

3.2. Noise Considerations

Optical amplifiers improve system performance when only a small amount of light reaches the WFS. However, additional noise is added to the system whenever such an amplifier is implemented. When the amplifying medium is pumped, ASE is emitted. ASE consists of broadband packets of photons excited within the gaining medium. This additional emission becomes background noise within the system. The power of this noise can be described as follows:

$$P_{ASE} = (k-1)NF\frac{\Delta\lambda c}{\lambda^2}\frac{hc}{\lambda}$$

Where k is gain, NF is the noise figure of the amplifier, λ is the nominal wavelength of the ASE, $\Delta\lambda$ is the width of the ASE spectrum, c is the speed of light, and h is Planck's constant. ASE is generally incoherent with respect to the reference and signal beam, although wavelengths near the signal wavelength will interfere and add beat noise to the SRI WFS measurements. Ina addition, ASE also adds background noise to the overall system and reduces the effective well depth of the WFS camera. Additionally, equation 1 shows that the noise from ASE increases linearly with gain. Depth of the interference fringes, however, increases as the $\sqrt{k}$. These effects imply a minimum detectable illumination level and a maximum gain value for the amplifier before ASE corrodes the benefits the amplifier provides. There are three general ways to mitigate ASE; reducing gain, lowering noise figure, or narrowing the bandwidth of the spectral filter. Reducing gain is counter productive; if boosting the intensity of the beam was not necessary, there would be no need for the amplifier or any of the additional components. Noise figure is associated with the manufacturing of a specific amplifier, and is theoretically limited to 3. The bandwidth of the spectral filter can be narrowed, though approaching the signal wavelength may begin to cut out the signal itself.

Beat noise is also an unavoidable aspect of ASE. While ASE is broadband and in general incoherent with respect to the reference beam, included in that spectrum is the signal wavelength. Passing through the spectral filter, this noise continues to interfere with the original beam. This phenomenon is called beat noise. Without an optical amplifier, this noise would not be introduced into the system. Results shown in section 6 illustrate the trade-offs between improved SNR performance using an optical amplifier and less introduced noise without introducing the amplifier in the first place.

4. OPTICAL AMPLIFIERS

Optical amplifiers receive a signal and send it through a gain medium, producing an output signal with increased power. Two optical amplifiers have been considered for use in the SRI WFS: the SOA and the EDFA. These amplifiers have unique trade-offs worthy of discussion. The major factors are: available gain, noise figure, optical path length, and cost.

4.1. Gain

An EDFA can provide gains up to 50 dB while an SOA has a gain on the order of 15-20 dB. A first glance at the values favors the use of an EDFA, but this higher range comes with a price. ASE is linearly related to gain; therefore higher gain implies higher ASE. With a signal small enough to warrant the high gain from an EDFA, the amount of ASE introduced into the system may degrade any improved fringe intensity with an equally increased background noise.

4.2. Noise Figure

The noise figure associated with an optical amplifier comes from several interactions between the signal and the gain medium. The lower the noise figure, the lower the minimum threshold of detecting the signal. Mathematically the noise figure is the ratio of the incoming SNR to the SNR of the amplified beam. Thus, amplifiers with lower noise figures are credited with better performance. The EDFA can have a noise figure of 3.1 dB, whereas a SOA typically produces a noise figure of 9-10 dB.

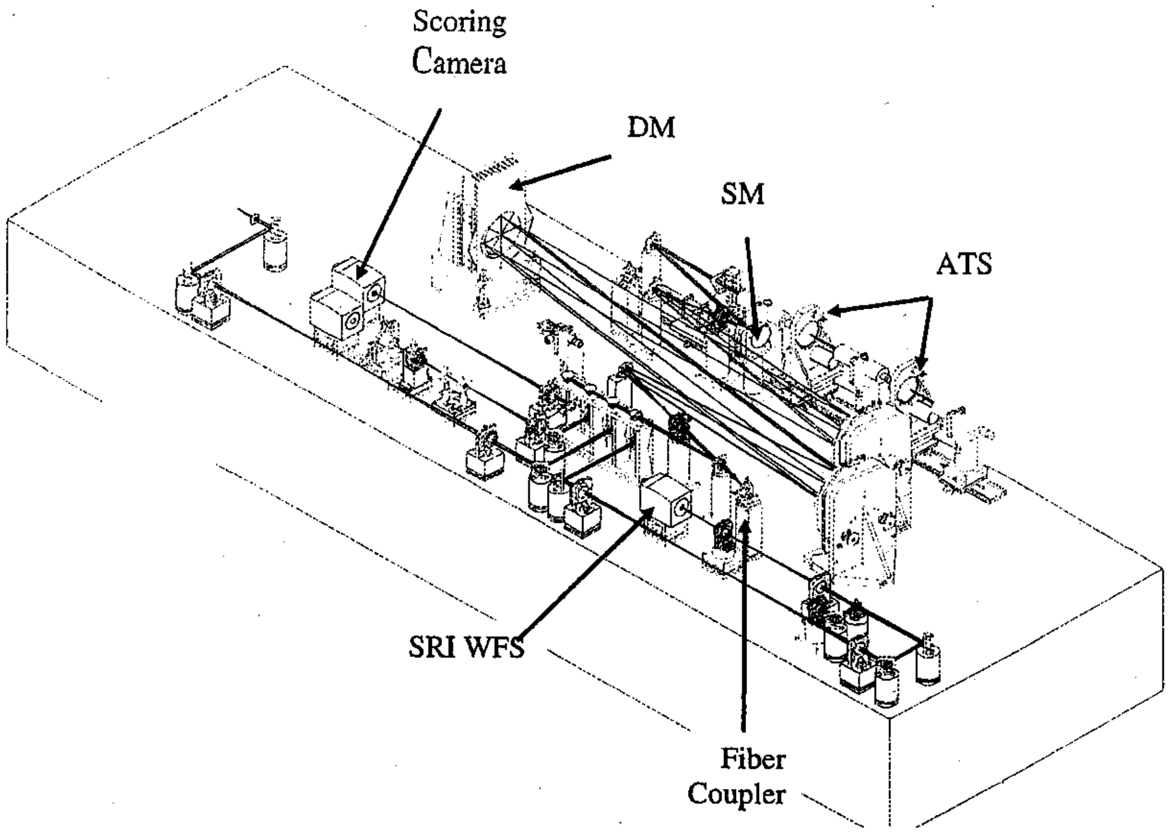

Figure 2. Diagram of the SRI WFS experimental setup.

4.3. Path Length

With the reference beam traversing a unique path, the signal must be path-matched to the reference path so that coherent beams arrive at the WFS camera. This path requires additional relay optics and table space. Depending on the length of the path, table space may become an issue, as well as maintaining mechanical stability of the additional optics. The SOA requires less than one meter of fiber to match the amplified beam path to that of the signal beam and to interface with the SRI WFS. A traditional EDFA requires upwards of 10 meters of fiber not only for the amplifier, but also for the signal leg to create the required path length to match that of the reference beam and produce interferometric fringes at the WFS camera.

4.4. Cost

While the above factors use performance as the primary metric, the last factor is a monetary consideration. The EDFA can cost upwards of $15 thousand, while an SOA typically costs 3 or more times less, at around $5 thousand. As mentioned in previous sections, additional components are necessary to the successful incorporation of an amplifier to the system. These components vastly differ in quality and complexity, and price will often scale with those characteristics, or highlight a lack thereof.

5. EXPERIMENT

A prototype SRI WFS has been developed at the Starfire Optical Range that currently serves as the interferometer in the Atmospheric Simulation and Adaptive-optics Laboratory Testbed (ASALT). An experiment to characterize performance of the SRI with an optical amplifier was conducted in the ASALT Lab. The optical layout of the ASALT laboratory is shown in figure 2. The first component of the ASALT Lab is the Atmospheric Turbulence

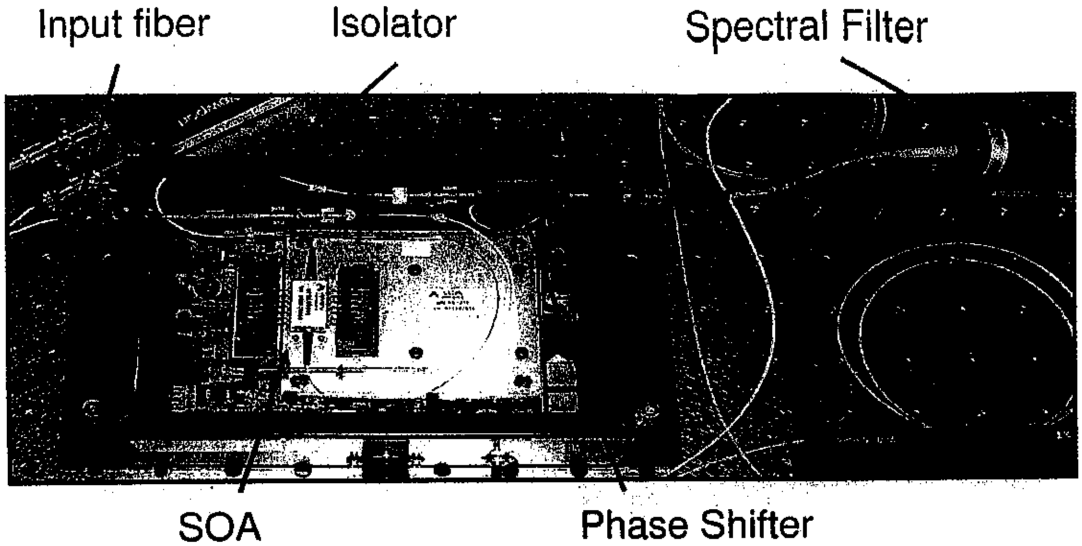

Figure 3. Fiber reference for the SRI WFS. The SOA and other fiber components are shown.

Simulator (ATS).[7] The ATS has two phase plates that represent a high altitude and low altitude layer of atmosphere. The phase plates, machined to reproduce turbulence with Kolmogorov statistics, are placed in between two back to back afocal systems. By changing the configuration of the plates, the Rytov number and value of r_0 can be varied and controlled in the laboratory environment. In addition, Greenwood frequency is controlled by changing the rate at which the phase plates rotate through the beam.

From the ATS, the beam is directed to a steering mirror. It is then relayed to a deformable mirror (DM). From there it is split into the reference and signal beams to begin the SRI WFS path as described in section 2. The DM used is a Xinetics 577 channel, continuous surface DM with 8 μm of stroke and 7.7 mm actuator spacing and 25 actuators across the pupil. The camera used as the SRI WFS interferometer is a near IR Indigo Pheonix 320x256 pixel array, sampled with 200x200 pixel sampling. This configuration allows for binning down, but gives a truth measurement at higher resolution. The optical amplifier used is shown in figure 3. It is an InPhenix SOA with maximum gain of 20 dB, a noise figure of 9 dB and fiber path length of approximately 50 cm. For EDFA testing, the SOA was removed and the EDFA inserted in its place. The EDFA used is a NP Photonics mini-EDFA. It has a noise figure of 3.4 dB, maximum gain of 39 dB, and a fiber path length of 68 cm. It is shown in figure ??.

5.1. Amplifier Testing

To characterize the effects of using an EDFA versus a SOA, we chose three illumination levels of light, ranging from a low level of 0.275 μW to 65 μW, which saturated the WFS camera. These values were selected by reading the full aperture power of the beam at the WFS. An attenuator placed in front of the ATS provided control for increasing and decreasing the light levels. The ATS was configured to simulate a scenario with Rytov of 0.5 and $\frac{d}{r_0}$ of 0.75. For every level of light, the beam ran through the turbulence and closed-loop data was collected. This process was repeated for four levels of amplifier gain. For the SOA, these values were 100, 150, 200, and 250 mA. To characterize the effects of the EDFA, the same process was implemented, replacing the SOA with the mini EDFA, shown in figure 4. For the EDFA the gain current values were 800, 830, and 850 mA. The EDFA and SOA values tested spanned the gains available for each amplifier. While three levels of illumination were tested, only the lowest two are used to compare performance of the EDFA against that of the SOA. With the EDFA, the maximum level of illumination saturated the WFS camera preventing true measurements of the interference fringes. With lower illumination levels, the relative intensity of the reference beam was so great compared to the signal beam that no fringes were detected on the WFS camera. As a result, no results for the EDFA can be presented.

Table 1. Experiment Parameters

$d_{actuator}/r_0$	.75
σ_χ^2	0.5
SOA Current (mA)	100, 150, 200, 250

5.2. Experiment Data Collection Procedure

Data for the amplifier testing was collected in standardized fashion. Through out testing the atmospheric scenario remained constant and is listed in Table 1. For each amplifier setting, 250 frames of data were recorded, of which 175 were closed loop data. For each setting, only one realization was recorded. To calculate Strehl, the last 150 frames of data were averaged and compared against a reference average. To simulate the best case scenario of SRI performance, the reference average was closed loop data collected with no turbulence.

5.3. SNR Estimation

The following analysis procedure was applied to all data collected to calculate the SNR of varying illumination levels. ASE background frames were captured for each amplifier level, where the signal beam was blocked before entry into the optical path. This isolated the ASE introduced into the system. These data frames were averaged to produce an ASE bias figure for each amplifier level. Additionally, the variance of this mean was calculated, using poisson statistics. Dark frames were also captured and the same process described above was applied to get an average value for the background noise. The value from the dark frames and the ASE bias frames were both subtracted from the signal value of the closed loop data for the corresponding amplifier level/illumination level data. This resulting value (I'_{SRI}) was then used to calculate SNR as follows:

$$SNR = \frac{I'_{SRI}}{\sqrt{I'_{SRI} + \sigma_{ASEBias}}}$$

The variance of the closed loop data was assumed to be the variance of the ASE bias. The variance was also assumed to be photon noise only. While this is not an accurate representation, it is not disproportionate by orders of magnitude and therefore a reasonable estimate.

6. RESULTS

The results of the amplifier testing are shown in Figures 4 and 5. Figure 4 shows the correlation between the the gain current and the resulting Strehl of the system. As the amplifier current increases, the amplification of the beam increases, resulting in improved performance of the system. The drop-off and leveling-off of performance at greater current values indicates that the system is starting to transition from a photon noise limited regime to a shot noise limited regime, indicating that the gain is now so high it is introducing noise into the system and overshadowing any benefit it is giving by boosting the signal intensity.

Figure 5 shows the relationship between current of the amplifier and signal to noise of the varying amplifications. As the amplification increases, the signal to noise increases. Referring back to Figure 4, the signal to noise improvement corresponds to an increased Strehl, verifying that performance is improving with increased SNR. At a signal to noise ratio of 1, the performance drastically improves. This level indicates the system is entering the photon noise limited regime of operation, the theoretical limit of operating performance.

Specifically reffering to the low level of light, SNR values above 1 occurred when operating the amplifier at currents above 150 mA. Strehls at and above this current correspond to .25 or better.

With the lowest level of light, an SNR of 1 didn't occur until more amplification was applied, closer to 175 mA. While only one realization prevents definitive conclusions, the trends of this illumination level at gain currents above 200 mA indicate that the photon noise limited region is ending and shot noise is beginning to degrade performance capabilities. This is evidenced by the slope of the SNR on Figure 5 shallowing, and a reversing from a positive to a negative slope for Strehl on Figure 4.

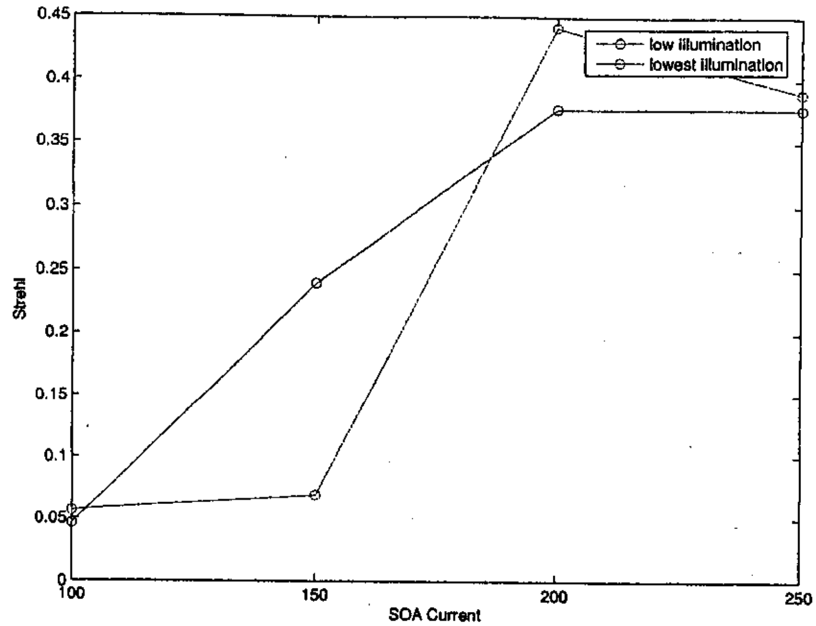

Figure 4. Strehl of varying SOA current values

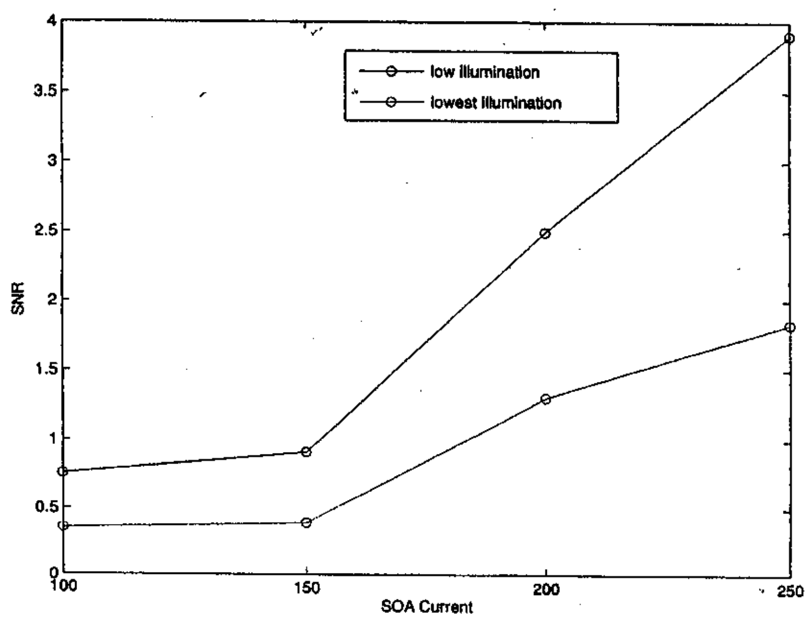

Figure 5. Signal to noise ratios of varying SOA current values

7. SUMMARY

In strong scintillation environments, optical amplification enhances signal detection and system performance. However, when light levels are intense enough, or when too much amplification is used, the resulting saturation of the WFS camera can degrade system performance. No EDFA data was presented in this paper, though an EDFA was tested in place of the SOA. At high illumination levels, the strong signal beam compounded by the amplification of the reference beam was so great it saturated the camera. At the lower light levels, the signal beam was so weak it went undetected at the camera. While the amplified reference beam could be detected at these low level regimes, interference fringes were not produced, preventing a successful closed-loop realization. Additional testing has been proposed, including removal of the amplifier altogether. Further testing will include determining a way to provide enough light for tracking purposes, and the EDFA testing will be re-conducted. Currently, the model used to estimate the SNR values is being modified and improved upon to achieve a more accurate realization.

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